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Controlled Heat Flux Combustor

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Abstract

A propane-fueled combustor was built to support the development of an alternate to the external fire test currently required for final hazards classification (HC). The device has the capability to provide a controlled heat flux environment of 20-200 kilowatts/square meter. This results in a repeatable and quantifiable environment for the evaluation of the fast cook-off response of an ordnance item.

Introduction

This paper presents a report on the design and development of a controlled heat flux combustor in support of a larger task aimed at the development of a sub-scale alternate test protocol to the external fire test currently required for final hazards classification (HC) of an ordnance system. The specific goal of this part of the task was to design a thermal stimulus which could be controlled and still deliver the flux levels encountered in a liquid fuel fire of the type related to transportation and storage.

Background

In the United States, all ordnance systems must be hazard classified. TB 700-2 is the documentation that is used for the hazards classification process (ref 1). The hazards classification procedures have been harmonized with both the U. N. Test and Criteria Manual for UN Series 1 through 1.4 (ref 2) and for the appropriate NATO STANAG (Ref 3,4). As described in TB70002, the ordnance system is hazard classified by performance of the system level tests listed in Table 1, or by performance of an approved alternate test, or by performance of an alternate plan which has received the approval of the appropriate service hazard classifier. Once the alternate tests have been performed, the results must be approved by the service hazard classifier and the DDESB.

Test
Single package
Sympathetic reaction
Liquid fuel/external fire

Table 1. HD 1.1 through 1.4 assignment tests.

Currently TB 700-2 contains three tests for explosive shock stimuli that have been approved as alternates for the system level test for sympathetic reaction, but there are no approved alternate tests for the liquid-fuel/external-fire test.

The liquid-fuel/external-fire test is described in NATO STANAG 4240. The item, in its shipping and storage configuration, is exposed to a liquid fuel fire. The fuel must extend a minimum of one meter beyond the edge of the item and be of sufficient volume to burn for 150 percent of the estimated time required to cause a reaction. The initial cost of a full-scale asset, the potential hazards associated with conducting the test, and the amount of real estate required for an appropriate test site, are some of the difficulties in performing the external fire test on large solid rocket motors. Since only one trial is required, the statistical significance of the test is questionable.

DDESB and the Joint Hazards Classifiers (JHC) have recognized the need for alternatives to the external fire test. They have supported the development of a technology base to achieve viable alternate tests.

Approach

A critical part of any alternate approach for thermal hazard classification is a heat source that can provide the appropriate heat flux levels over the appropriate time intervals and in a controllable and reproducible manner. A hierarchical or top down approach has been used in the design and development of the controlled heat flux device (Ref 5,6). A top down diagram related to the development of the current device is shown in Figure 1.

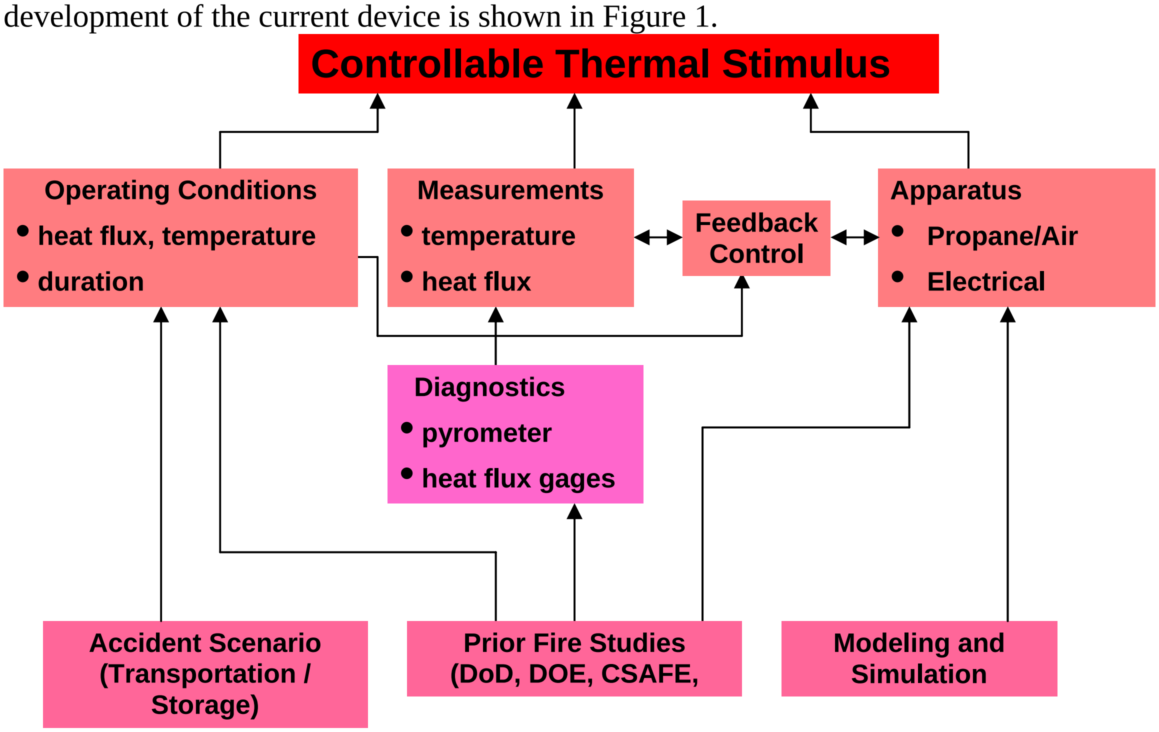

Figure 1. Diagram for development of controllable thermal stimulus.

The derivation of the thermal heat flux requirement was initiated with a review of accident data from the Department of Defense Explosive System Safety Mishap database, ESSM. Those findings were reported in the 31st United States Department of Defense Explosives Safety

Seminar of 2004 (ref 7). Data from related fire studies throughout the DoD, DoE and academia were also utilized, particularly, the ASCII sponsored work of the CSAFE program (ref 8).

The results of these investigations indicated that thermal flux levels of 20 to 200 kWatt/m^2 could be obtained during a thermal event, with the potential for that range of flux levels to exist simultaneously in the fire (ref 9, 10). These data validated the conclusion that a controllable flux device was needed for these studies to be effective. The device must also be tunable to allow for a range of heat flux values to be obtained. For the current effort, flux levels of 50, 75 and 100 have been selected for study. It should be noted that in the case of a fast cook-off event, the lower flux levels and longer thermal soak times may represent the most violent reactions, due to the involvement of a larger amount of energetic material in the cook-off event.

Apparatus

The physical nature of a fuel-fire is very difficult to quantify and measure. Understanding how the heat flux is coupled from the fuel fire flames to a specific target is important to experimental and computational modeling efforts in this area. The controlled heat flux device was conceived to provide the basis for a small-scale fuel-fire test for hazard classification and to probe the underlying physical response to the external fire test in a controlled manner. Options that were considered for the test device were electric resistive heating, radiative heating and propane/air. All of these devices have positive and negative features and are under development at a number of research facilities.

The electric resistive heating approach was rejected because of the concerns that an appropriate heating rate could not be achieved and that the need for contact with the test vehicle might interfere with the response of the item relative to violence. Radiative heating was also rejected due to the overall cost of the system. The propane-fueled combustor was selected due to its ease of construction at reasonable cost. The apparatus will allow for the study of both convective and radiative heating.

The apparatus is intended to apply a uniform and constant heat flux level to a small-scale sample so as to simulate the thermal penetration of heat flux experienced by a full-scale device in a fuel fire. The device seeks to be controllable, tunable, and variable in its rate of heat flux application. It has both reusable and expendable sections and provides a method of assessing the reaction violence with fragmentation of a portion of the test section.

Design

The schematic of Figure 2 shows the major components of the combustion device and how those components provide the means necessary for the combustor to operate. ***Air*** enters the ***combustion chamber*** via a duct at a flow rate determined by the required operating heat flux conditions. ***Fuel*** is injected at a location in the air duct so that the fuel can be mixed with the air, which will provide a flammable mixture. This mixture is then ignited in the ***combustion chamber*** at which time the fuel is consumed in the ***reaction region***, generating high temperature gas products. The combustion chamber has an inside diameter which is larger than the air duct. The change in area from the smaller air duct to the larger ***combustion chamber*** allows flame

stabilization for the ***reaction region***. The amount of fuel and air introduced into the chamber controls the gas temperature and therefore the heat flux.

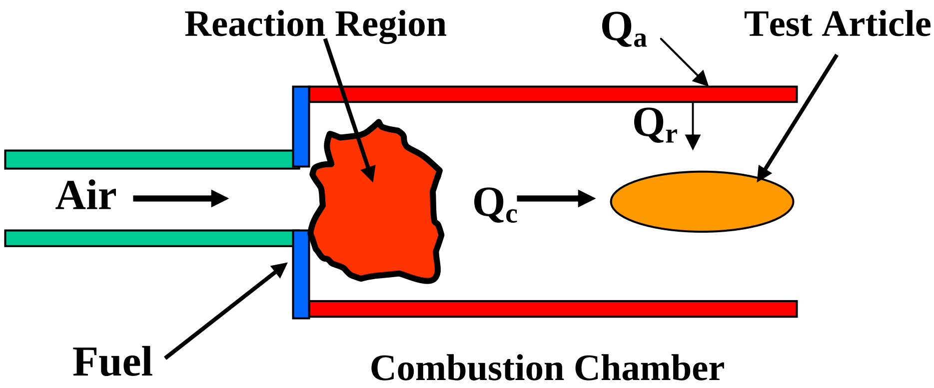

Figure 2. Basic Schematic of controlled heat flux device.

The ***test article*** contains energetic material that will be subjected to a controlled heat flux for evaluation. The heat flux is generated by two components in the combustion chamber. One component of the heat flux is the convective (**Q_c**) high temperature gases from the combustion products, while the second component is from radiation (**Q_r**) generated from the high temperature wall surface. The wall surface can be heated to the required temperature by the high temperature gases of the reaction region, or can be augmented by introducing additional heat (**Q_a**) to certain areas of the combustor wall.

The nonexpendable portion of the controlled heat flux combustor is shown in Figure 3. A five horsepower fan motor (Figure 4) delivers air through a 12.7 cm (5 inch) diameter stainless steel (schedule 5) air duct. The fan, when driven at 3870 RPM will deliver a mass flow rate of ~0.5 kg/sec (l lb/sec). Fuel is introduced through an aluminum manifold located at the end of the tube via eight injectors as shown in Figure 5. An array of eight injectors was selected to provide uniform fuel distribution. Liquid propane injection is shown in Figure 6.

Figure 3. Nonexpendable portion of the controlled heat flux combustor

Figure 4. Controlled heat flux combustor blower fan

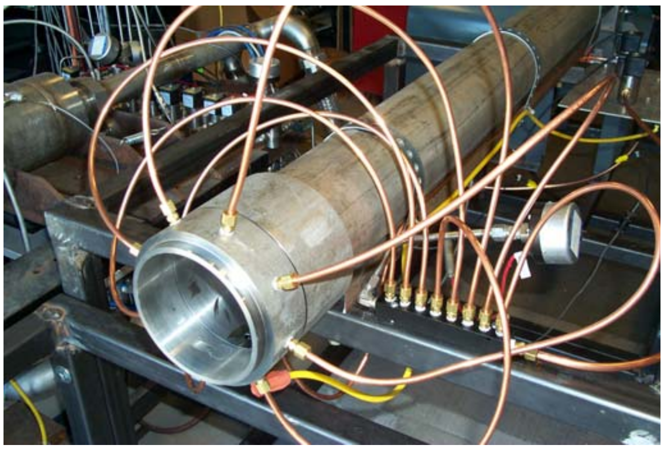

Figure 5. Fuel injection ring

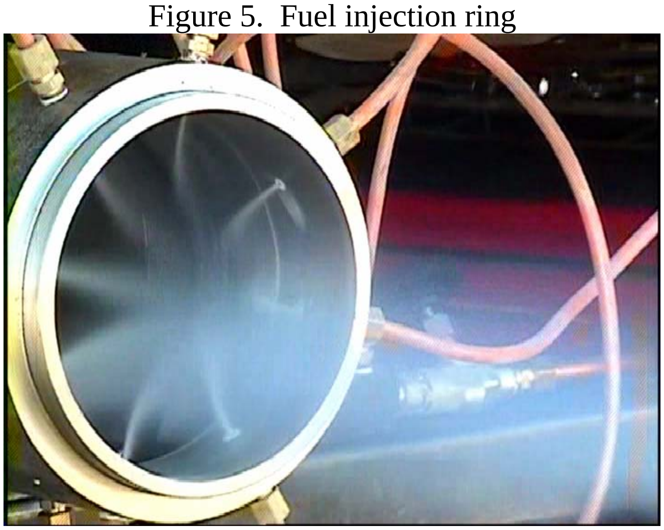

Figure 6. Liquid Propane injection.

The fuel/air mixture expands into an 0.46 m (18 inch) diameter stainless steel combustion chamber. The non-expendable portion of the chamber is approximately 2 meters (6 feet) in length. An additional 2 meters (6 feet) of combustion chamber represents the expendable portion

of the test apparatus and will act as a witness tube should fragmentation occur during the experiment.

Challenges

To provide the necessary heat flux in the present combustor it was decided to supply the propane fuel as a liquid in order to generate the 1-megawatt of power. With an approximate flow rate of 3 liters (1500 grams) per minute, a device capable of generating 10 kilowatts of power would be required to vaporize the liquid if gaseous propane had been chosen for this device. Another consideration is that the resulting expansion from the liquid to gas phase would also need much larger plumbing for the gaseous injection into the combustor. The volumetric increase of propane from liquid-to-gas is a factor of 254.

The vapor pressure of the stored propane should be adequate for the fuel delivery to the combustor at ambient pressure. At 0 Celsius, the pressure is 54 psig and at 50 Celsius, the pressure is 230 psig. However, tests conducted at various times of the year, when outside temperatures varied from 0 to 50 Celsius, concluded that the fuel system could not operate reliably at the low vapor pressure. Because the fuel delivery pressure must be reduced from the vapor pressure in the storage tank to the ambient pressure in the combustor, a phase change occurs at the fuel-metering orifice resulting in a 2-phase flow in the fuel distribution manifold. The resulting expansion of the gas phase created a very unsteady and unreliable flow rate in the injection system. A solution is currently being tested with a redesigned regulation orifice and distribution manifold. This system utilizes a fixed orifice for the pressure reduction and mass flow control. The placement is critical due to the requirement that an immediate volume increase be present to accommodate the partial expansion of the gas phase. Since propane is a refrigerant, those characteristics are used to condense the gas portion of the 2-phase mixture back to liquid only. This is accomplished by utilizing the latent heat of vaporization provided during the partial expansion process. The temperature in the aluminum distribution manifold is now lowered enough by this cooling that the gas can condense because the local vapor pressure is reduced.

While the present design does not allow for fuel adjustment during a test, it will provide enough information to construct a device that will have controllability to maintain a desired heat flux condition

Results

The expendable combustion chamber was omitted for the initial controlled flux testing. Eight Type K thermocouples were located along the exterior wall of the combustion chamber ~ 0.23 m (9 inches) apart. These thermocouples were used to evaluate the position of flame attachment in the combustor and to gain insight into the level of heat loss to the combustor wall. An additional type B thermocouple in a ceramic housing was located at the exhaust as shown in Figure 7. The external wall temperatures are compared to the exhaust temperature for a typical run in Figure 8.

Figure 7. Controlled heat flux combustor operating at 1400 degrees C.

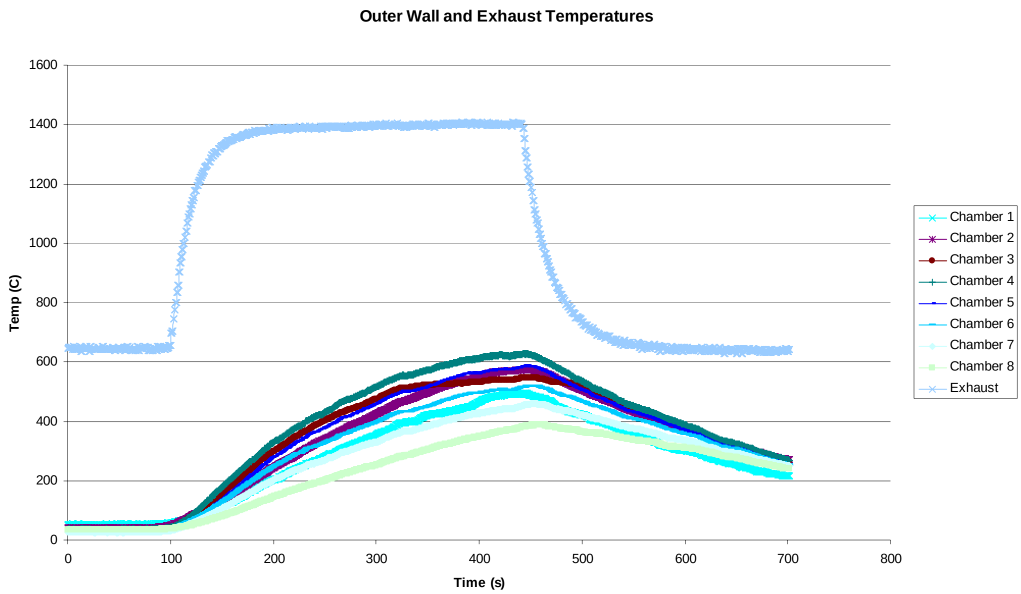

Figure 8. Temperature versus time data for controlled flux combustor operation

This test was run for approximately 5 minutes at a temperature (1400 C) to check out the maximum operating capabilities of the device. This time duration was long enough to verify a uniform gas temperature and to evaluate flame location without potentially damaging the combustion chamber pipe. The exhaust temperature in Figure 8 shows a time lag to steady state conditions of 100 seconds. The observed lag is due to the slow response of the type B thermocouple used for this measurement. The thermocouple was an industrial version with a large massive protective ceramic enclosure that would have a very slow response time. The temperature steady state condition is most likely several seconds and will be measured later with a fast response 10 mil thermocouple. An important consideration for thermal lag of the system would be the time to heat the mass of the walls to provide the radiation component of the heat flux. This will also be measured later by a calibration device.

External temperatures of the wall-mounted thermocouples at three different times are given in Figure 9.

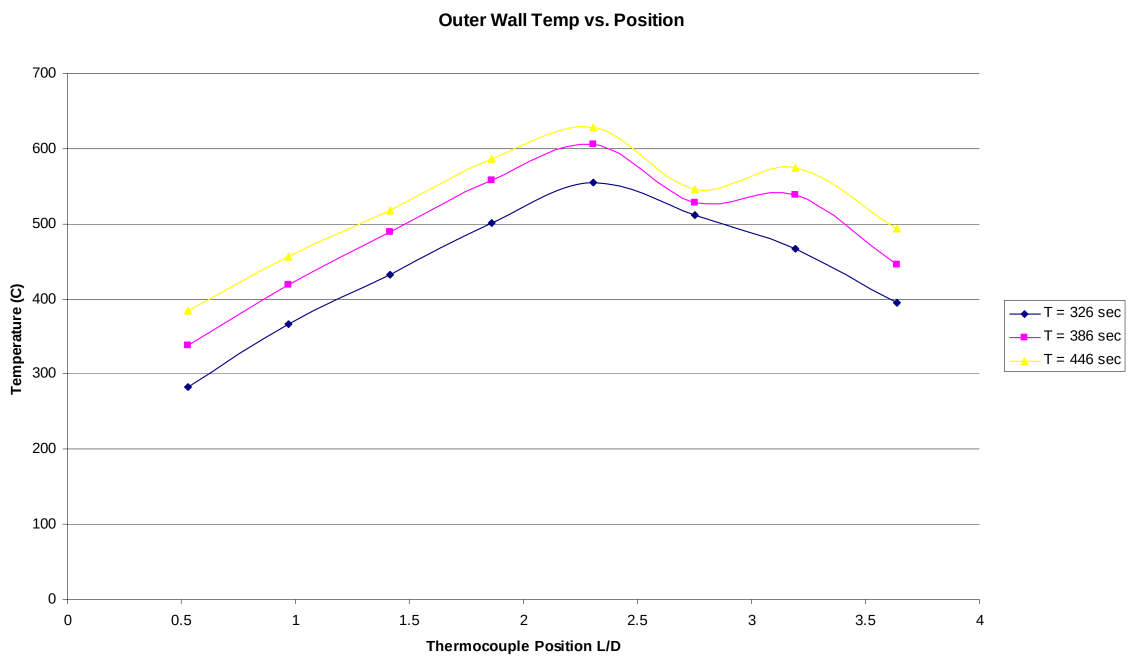

Figure 9. Temperature of wall mounted thermocouples

Calibration

To determine the overall heat flux output of the device, calculations at mass flow rates of 0.55, 1.1 and 1.65 lbs/sec were made using FLUENT (ref 11). Heat flux versus temperature from the calculations are plotted in Figure 10. A heat flux of 160 kW/m^2 can be obtained for an exhaust temperature of 1500K at a mass flow rate of 0.5 kg/sec (1.1lbs/sec). These calculations illustrate that the convective and radiative components of the total heat flux can be changed with adjustment of the mass flow rate.

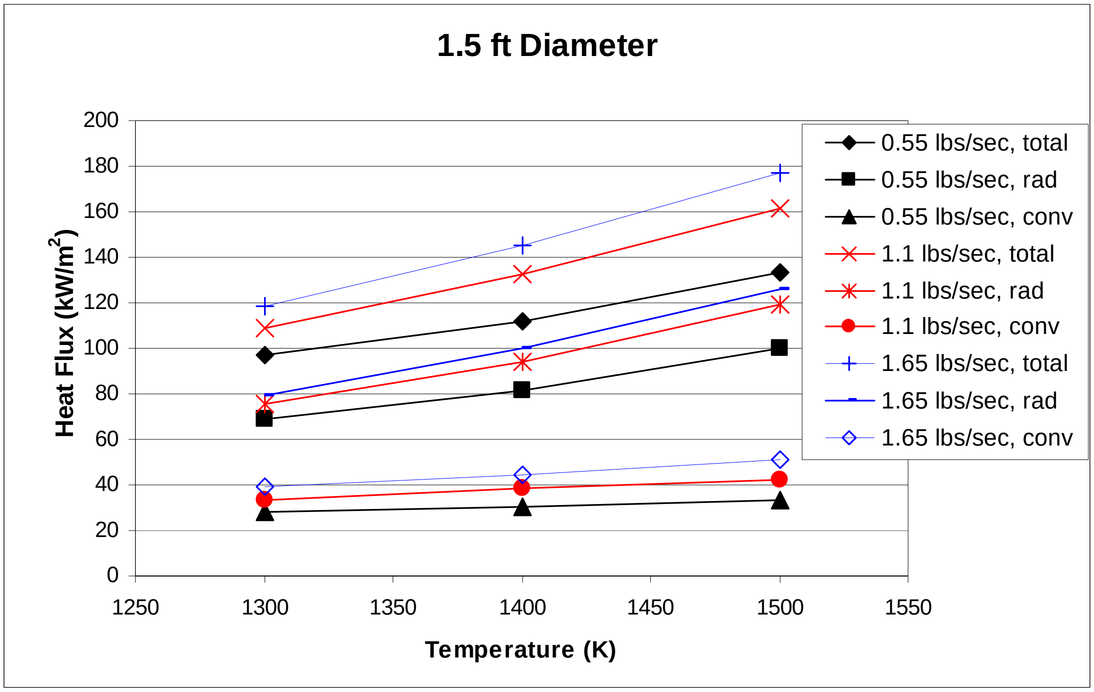

Figure 10. FLUENT calculations of exhaust heat flux.

The above calculations are useful in assessing the overall design capabilities of the device, but they do not provide information on the heat flux at the location of the test article. In order to do that, a calibration tool is being designed to make heat flux measurements at the test article position. Modeling and simulation tools are again being utilized in the design of the calibration fixture. Figure 11 gives a concept of the calibration tool that is currently being constructed. The calibration device will have the same exterior shape as the test article. The calibration device (and test article) will be fitted with a flow diverter nose cone, which will provide a uniform heat flux along the cylindrical wall of the device. The calculations indicate that a 10-inch flow diverter is needed for uniform thermal flux. The cylindrical portion of the device is being fitted with six water-cooled Vatell heat flux microsensors (ref 12). These sensors were selected because they will operate in a cross flow condition. The cylinder will be water cooled to allow the microsensors to function properly over the entire temperature range. The mounting cylinder will be five inches in diameter as it was determined that the heat flux microsensors could not be mounted in a smaller diameter. Overall length of the cylindrical portion of the calibration unit is ten inches.

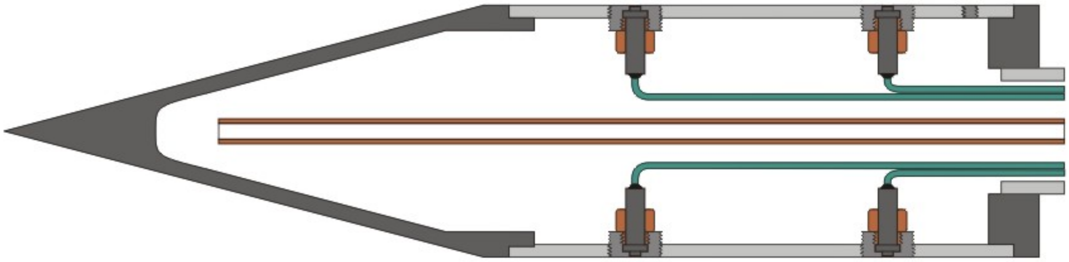

Figure 11. Concept of the test vehicle calibration tool.

Conclusions

A controllable heat flux device has been designed and assembled. The test fixture was constructed in support of an ongoing effort to develop an alternate test protocol to the external fire test required for final hazard classification of ordnance systems. The device will be used to examine the effects of thermal flux on the response of an ordnance device in a controlled environment.

Modeling and simulation tools were used to design the apparatus and provided aid in its construction. The device consists of a modular design so that modifications can easily be made as needed. The modular construction allows for transportation of the device to remote test locations.

The controlled heat flux combustor is constructed from parts that are readily available, and is repairable when damage occurs. A portion of the combustor is designed to act as a witness tube for evaluation of reaction violence. No single part of the controlled heat flux device exceeds $1000 in cost. The diameter of the chamber is 46 cm (18 inches) and should accommodate a test article up to 23 cm in diameter (9 inches). The length of the test article is dependent upon the ability to support the device and the amount of heat loss encountered in the increased chamber length.

The controlled heat flux combustor operates with liquid propane, a readily available fuel with a high energy density. The fuel is self pressurized. The combustor does not require high-pressure air for mass flow rates up to 0.5 kg/sec (1 lb/sec). The heat flux is a combination of radiation emitted from the chamber walls and convection from the 3 m/sec gas flow within the combustor Adjusting the total mass flow rate and/or the temperature of the mixture controls the power level of the test fixture.

Future Plans

The new fuel injection manifold design has been installed and testing is in progress to assure reliable operation of the system. The calibration tool is being manufactured and calibration at the test article location will commence upon its completion. Once the calibration of the system is complete the controlled heat flux device will be relocated to the remote test site where the evaluation of energetic materials will begin.

The controlled heat device will be used to provide the necessary thermal data on the mechanistic variables that are associated with cook-off reaction violence. The ability to control the heat flux will result in data that are reproducible and of sufficient fidelity to be input into the analytical tools currently being used to design a viable alternate thermal test.

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